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Measurement of high frequency surface pressure fluctuations for blade noise characterization

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Measurement of high frequency surface pressure fluctuations for blade noise characterization

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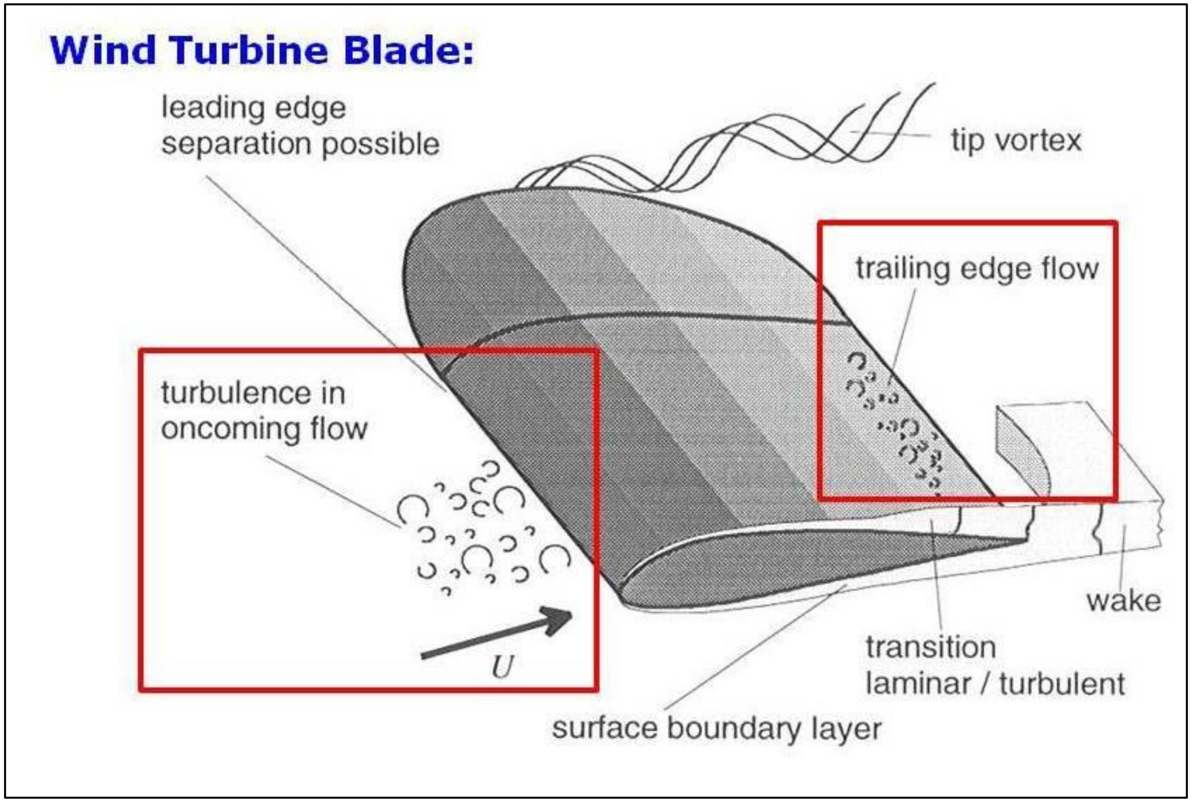
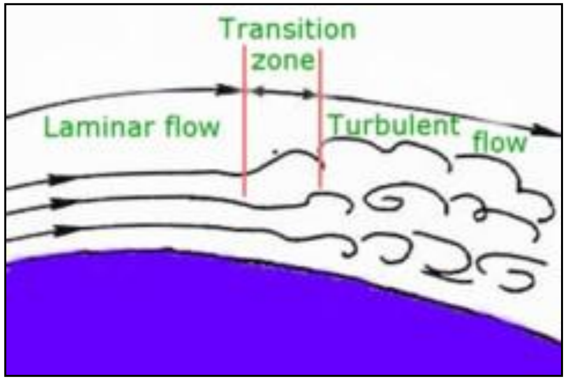
Outline

- Why using high frequency surface pressure measurements ?
- Surface pressure to far field noise
- Measurement technique
- Wind tunnel measurements compared with model results
- Measurements on a full scale 80m diameter rotor
- Influence of different inflow conditions on the noise source
- Perspectives for application of the technique

Why using high frequency surface pressure (SP) measurements for aeroacoustic characterization ?

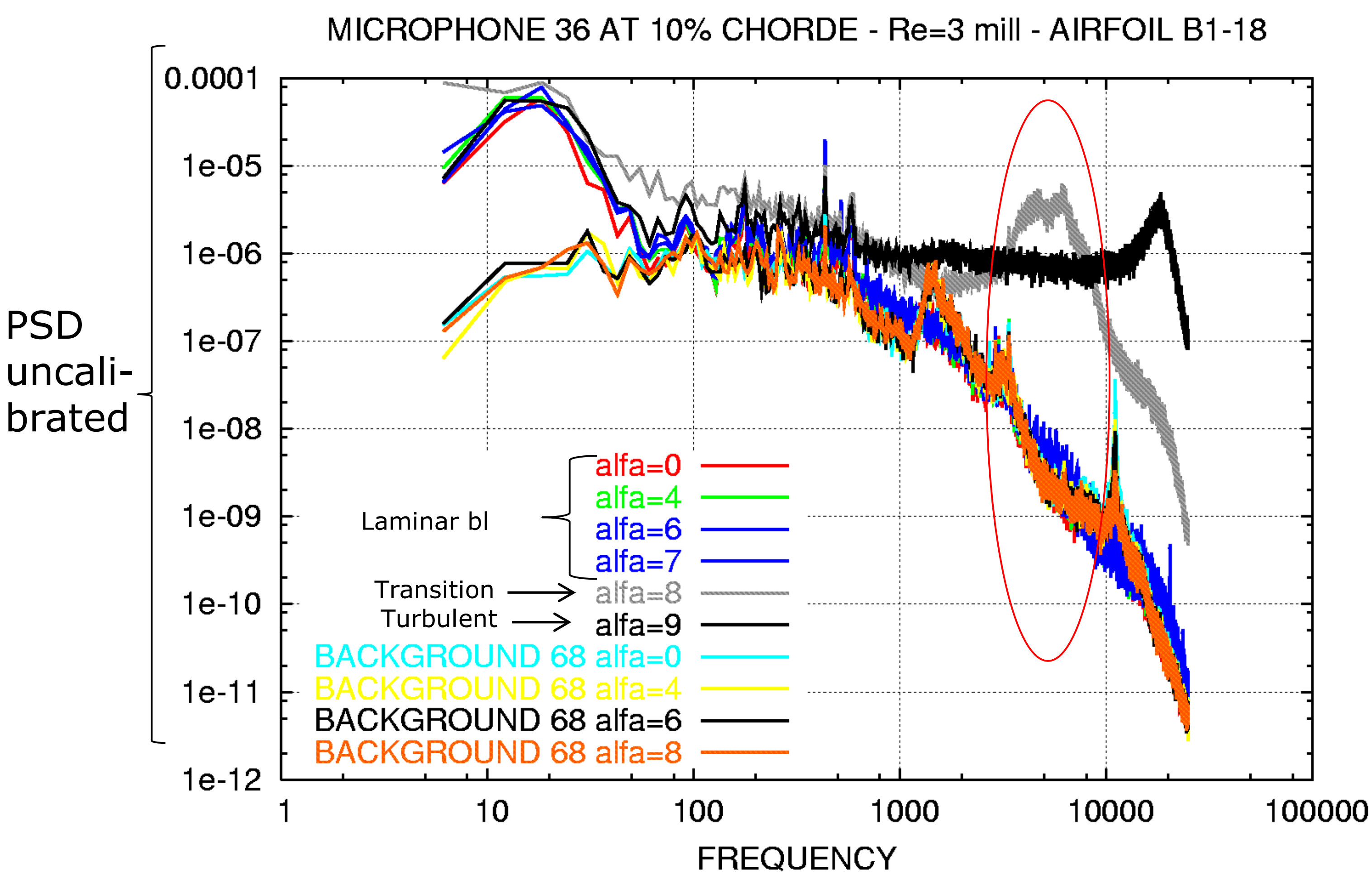
- SP is the source of trailing edge (TE) noise
- SP is the source of turbulent inflow (TI) noise
- SP has a high intensity compared with ambient noise



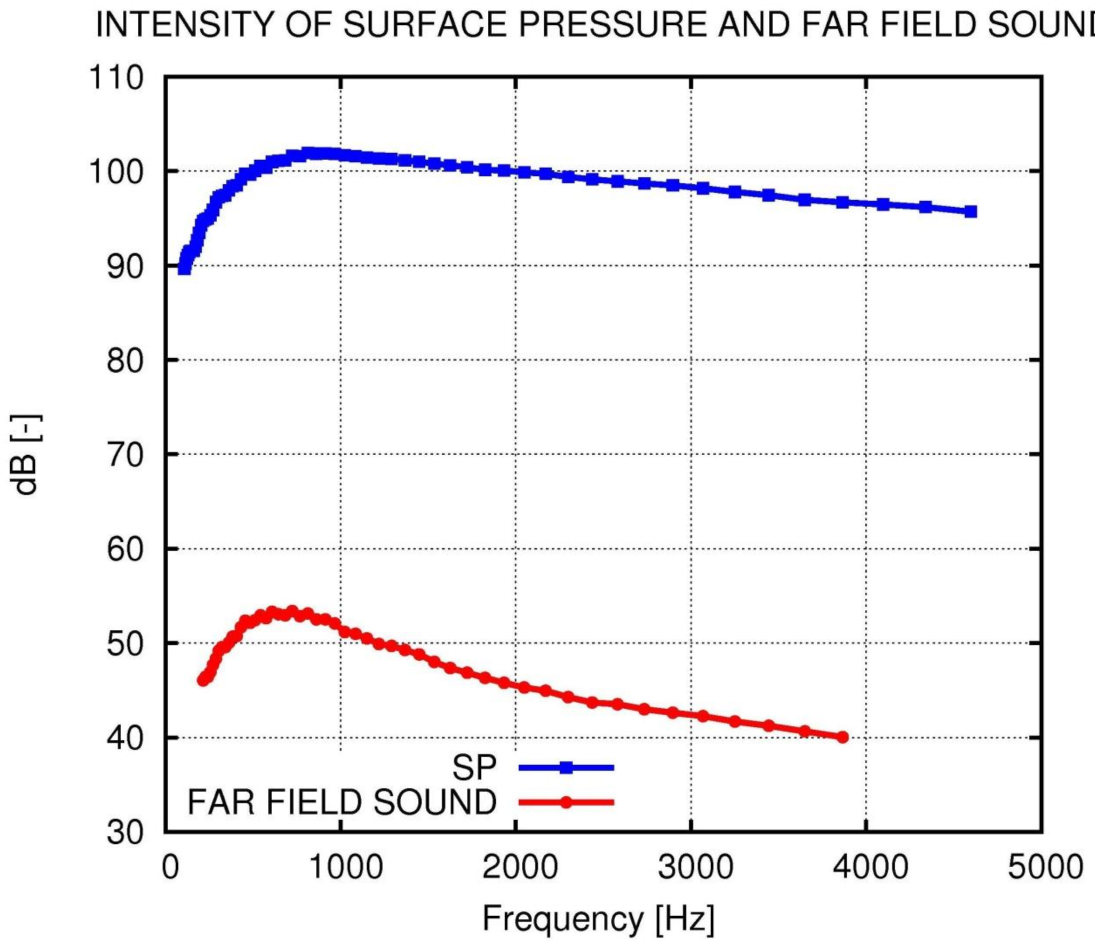


- Measuring SP enables correlation with detailed inflow data from inflow sensors on the blade
- Measuring SP provides more accurate aeroacoustic characterization during design and testing of new low noise airfoil designs
- Measuring SP provides detailed noise source information, enabling continuous, optimal input to the turbine control system for operation within noise constrains

SP in a turbulent boundary layer has a high intensity compared with ambient noise



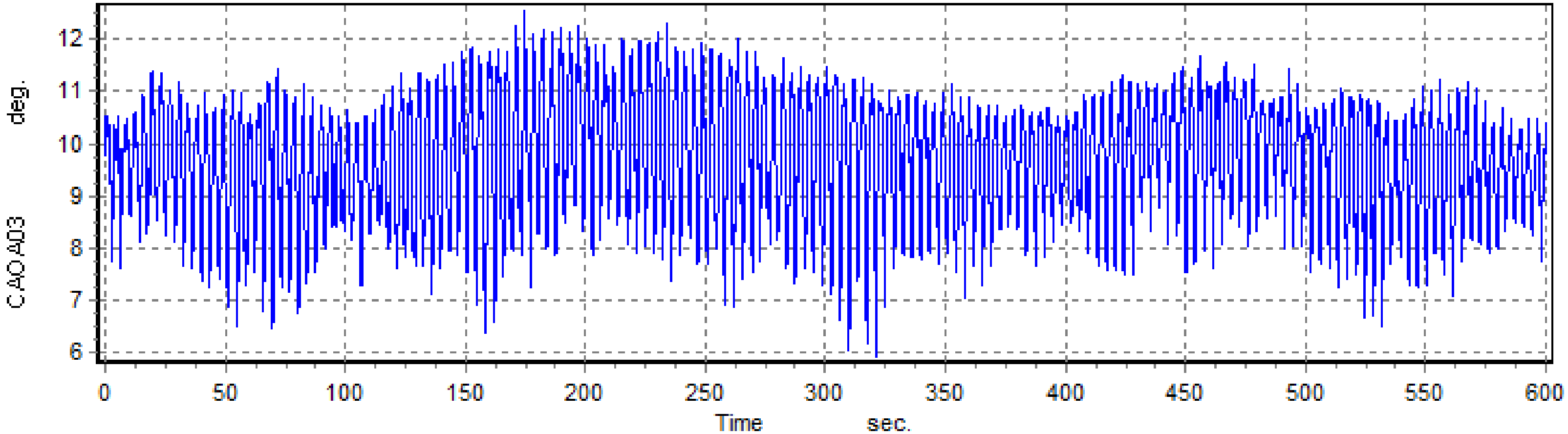
SP in the turbulent boundary layer has a high intensity compared with the farfield sound

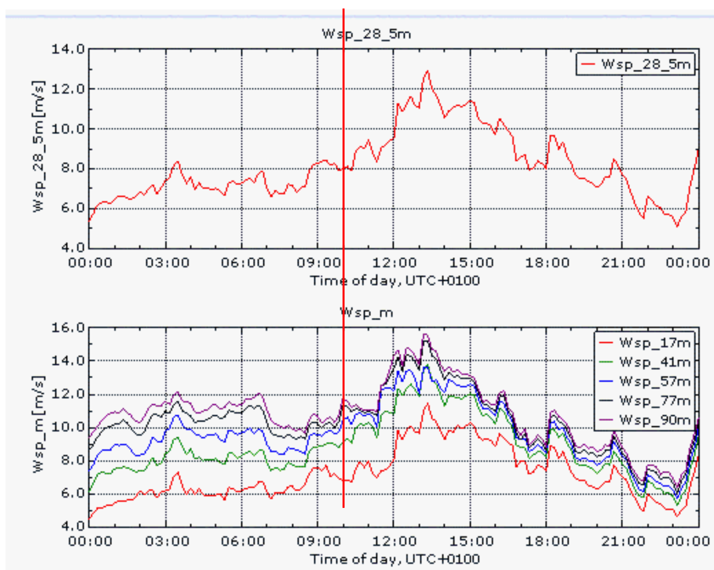


Based on set-up in the Virginia-Tech Wind Tunnel 2011 – NACA64-618 airfoil at 1.5 mill Re

The inflow to the blade is varying considerably in time, in particular over 1p -the same is the noise source

Measured inflow angle at radius 30m on a 2MW turbine



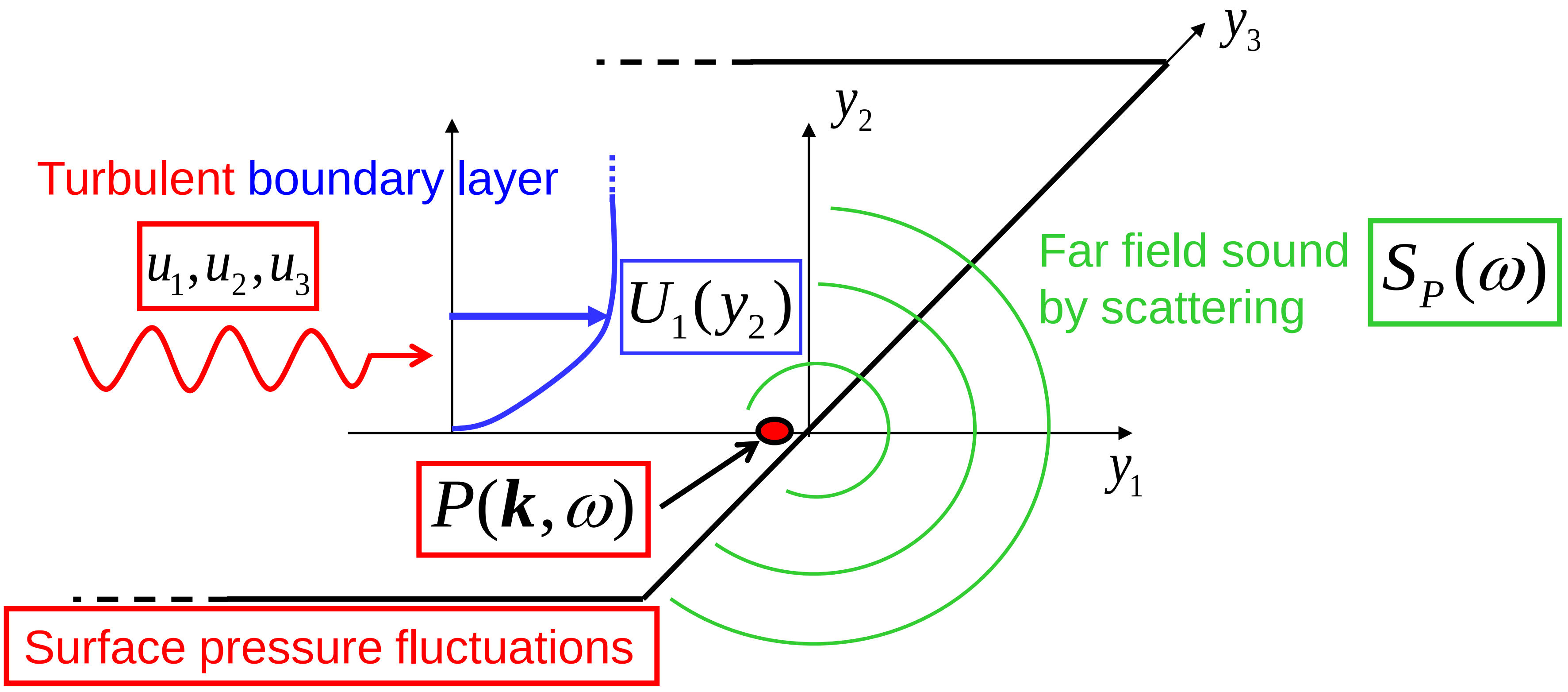


Drawbacks with the SP technique compared with traditional far field measurements

- it is measurements at a cross section of a blade
- uncertainty in converting the SP to the far field noise
- …….

Surface pressure to far field noise

TE Noise Mechanism



Using TNO model & CFD to evaluate: $P(\boldsymbol{k} = \{k_1, k_3\}, \omega)$

TNO model* + CFD RANS Calculation

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…yield SP spectrum (Blake, 1986):

$$P(\boldsymbol{k},\omega) = 4\rho_0^{\ 2}\,\frac{k_1^{\ 2}}{k_1^{\ 2}+k_3^{\ 2}}\int_0^{+\infty} L_2(y_2)\left(\frac{\partial U_1}{\partial y_2}\right)^2 \overline{u_2^{\ 2}}\cdot\Phi_{22}(\boldsymbol{k},\omega)\cdot\Phi_m\left[\omega - U_c k_1\right]\cdot \mathrm{e}^{-ky_2}\,\mathrm{d}y_2$$

Isotropic turbulence

$$\frac{L_2}{0.745} = \Lambda = 0.519\cdot\frac{k_T^{3/2}}{\varepsilon}$$

Empirical approx.

$$\overline{u_2^2} = 0.45\cdot k_T$$

Von Karman Isotropic Spectrum

$$\Lambda = 0.519\cdot\frac{k_T^{3/2}}{\varepsilon}$$

In-house CFD RANS code EllipSys2D

* modified TNO model:

F. Bertagnolio, Experimental Investigation and Calibration of Surface Pressure Modeling for Trailing Edge Noise, in: Proc. of Inter-Noise 2011 Conf., Osaka, Japan.

TE Noise Evaluation from SP Spectra

- **Far-Field Noise (Howe, 1978):**

$$S_P(\omega) = \frac{L_{span}}{4\pi R^2} \int_{-\infty}^{+\infty} \frac{\omega}{c_0 k_1} \cdot \underline{P(k_1, k_3 = 0, \omega)} \, \mathrm{d}k_1$$

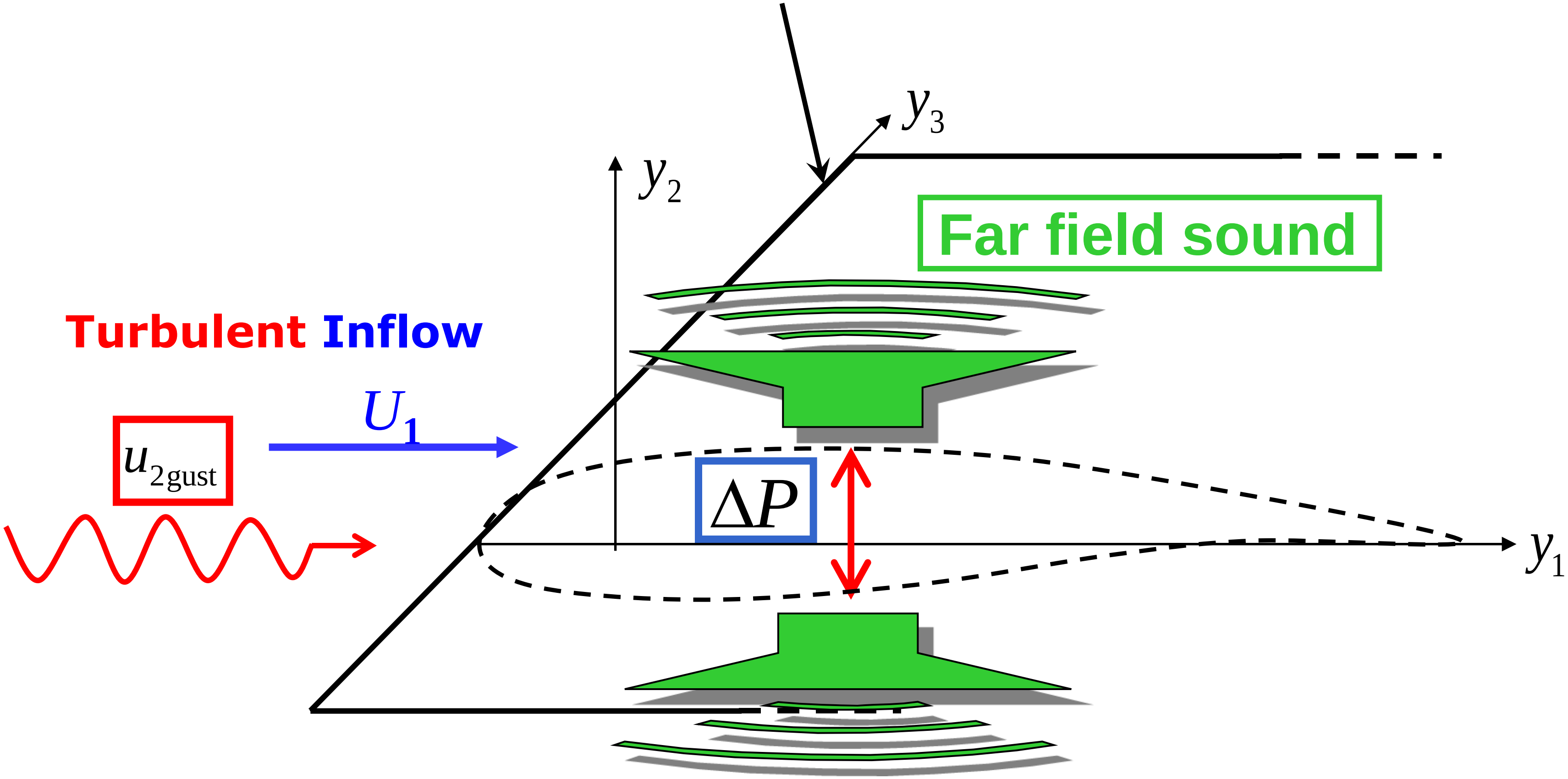
- **Surface Pressure *Frequency*-Spectrum:**

$$P(\omega) = \iint_{-\infty}^{+\infty} \underline{P(k_1, k_3, \omega)} \, \mathrm{d}k_1 \mathrm{d}k_3$$

Measured by HF mics.

Turbulent Inflow Noise

Idealized Airfoil as an Half-Plane

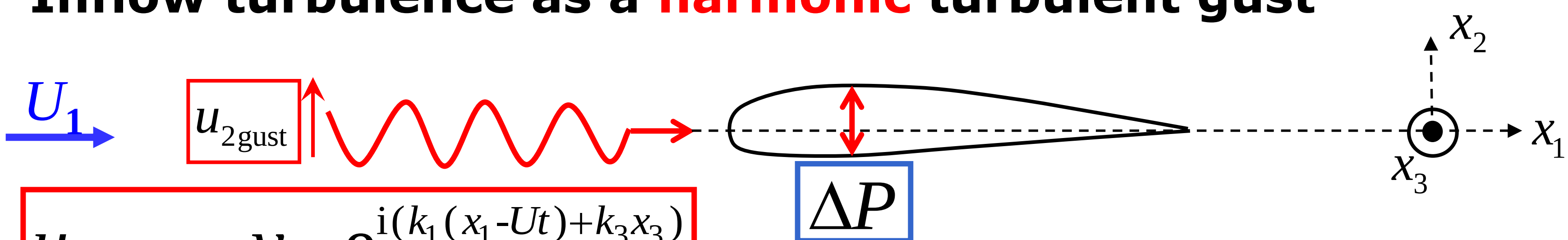


Turbulent Inflow Noise Model

Amiet's Theory (1976)

Linearized Inviscid Theory *for* *flat plate* *with* *0-mean loading*

- **Inflow turbulence as a harmonic turbulent gust**



$$\boxed{u_{2,\text{gust}} = v_0 \cdot \mathrm{e}^{\mathrm{i}(k_1(x_1 - Ut) + k_3 x_3)}}$$

- **Surface pressure response using Sears' theory:**

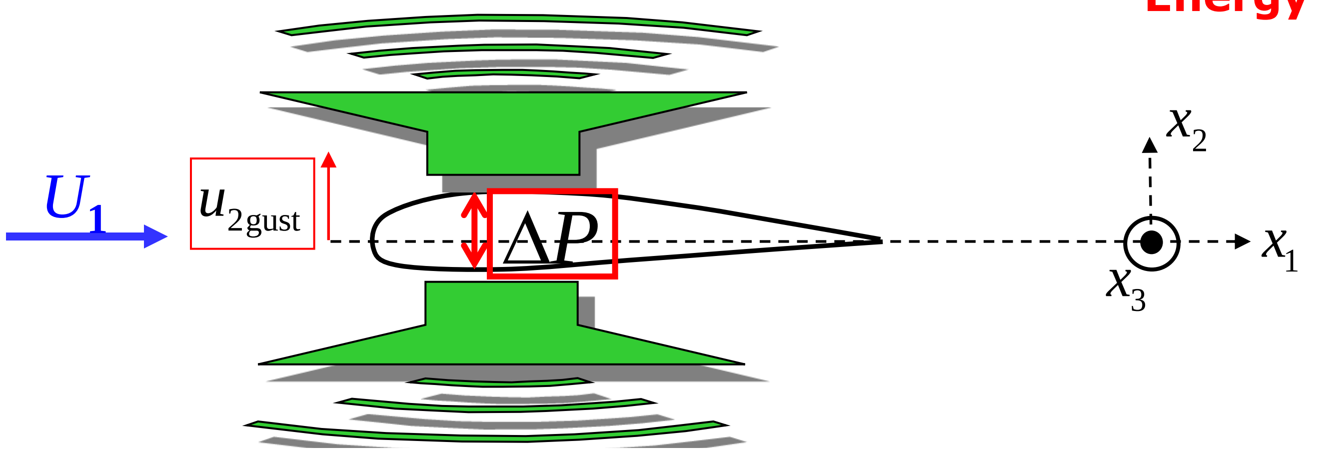
$$\boxed{\Delta P(x_1, x_3, t, k_1, k_3) = 2\pi\rho_0 v_0 \underline{g(x_1, k_1, k_3)} \cdot \mathrm{e}^{\mathrm{i}(k_1 U t - k_3 x_3)}}$$

where *g* is the transfer response function

Turbulent Inflow Noise Model

The energy spectrum of the local airfoil surface pressure jump fluctuations then reads:

$$\Phi_p(x,\omega) = 2U(\pi\rho)^2 \int_0^\infty g^*(\xi,K_1,k_3)\cdot g(\xi,K_1,k_3)\underbrace{\Phi_{22}(K_1,k_3)}_{\text{Energy spectrum of } u_{2gust}} dk_3$$



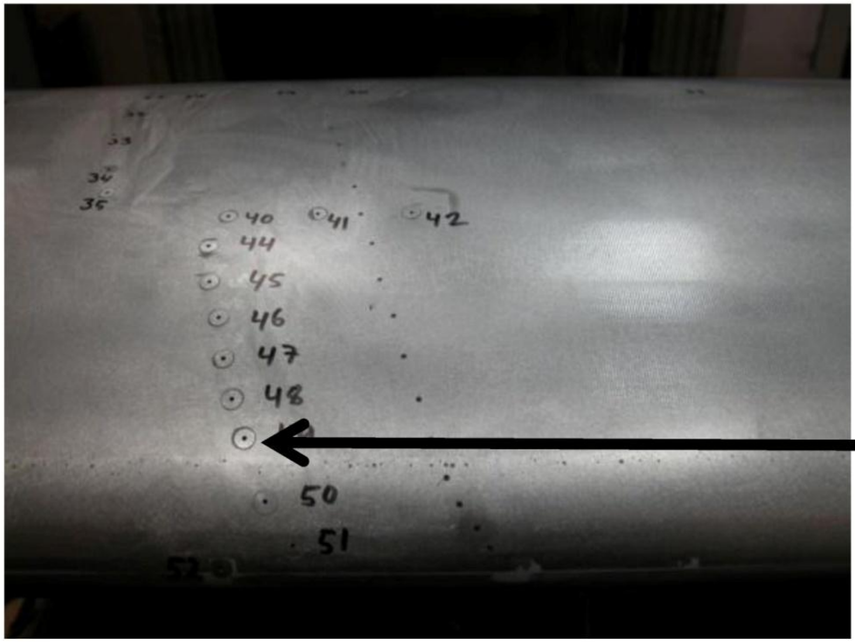
Pressure jump fluctuations radiate as dipole to far field noise

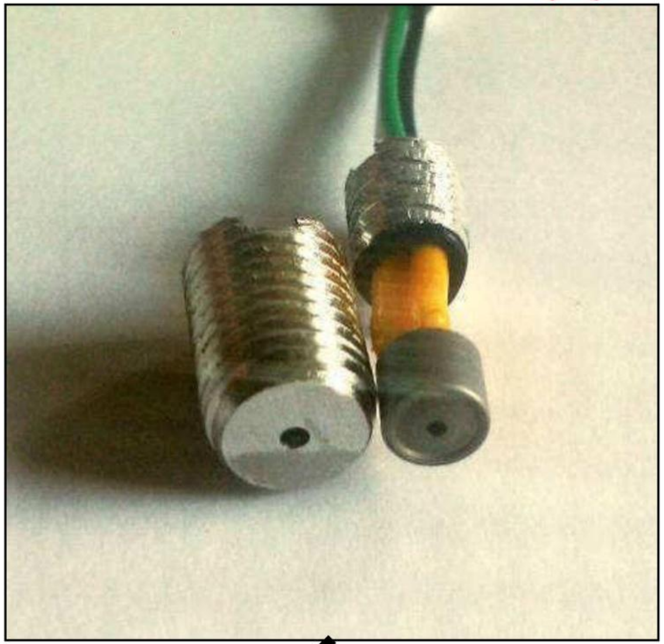
$$S(r,\omega) = \left(\frac{\omega\rho b y}{c_0\sigma^2}\right)^2 \pi U d\,|L(r,K_1,K_3)|^2\,\Phi_{22}(K_1,K_3)$$

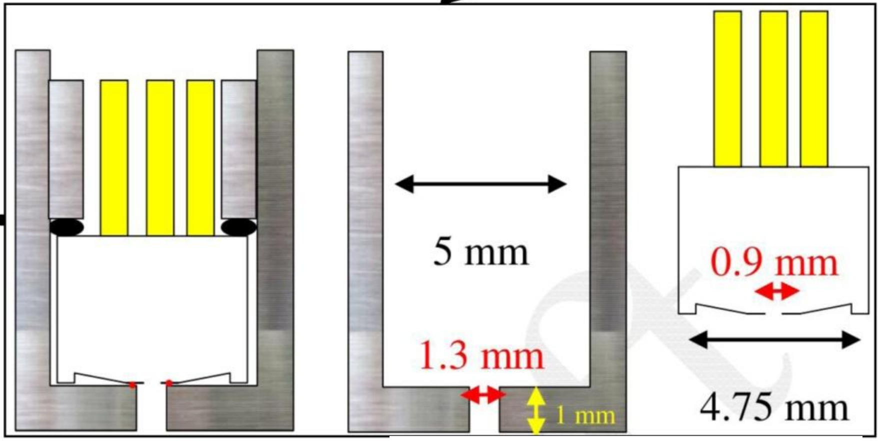
The measurement technique

SURFACE PRESSURE – Meas. Technique

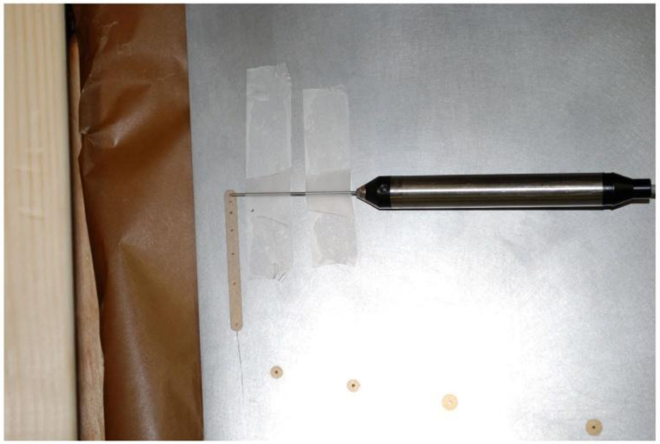
Flush-mounted HF microphones







Calibration of microphones in cooperation with B&K



(a) reference microphone and pinhole

(b) Sennheiser headphone HD650 source

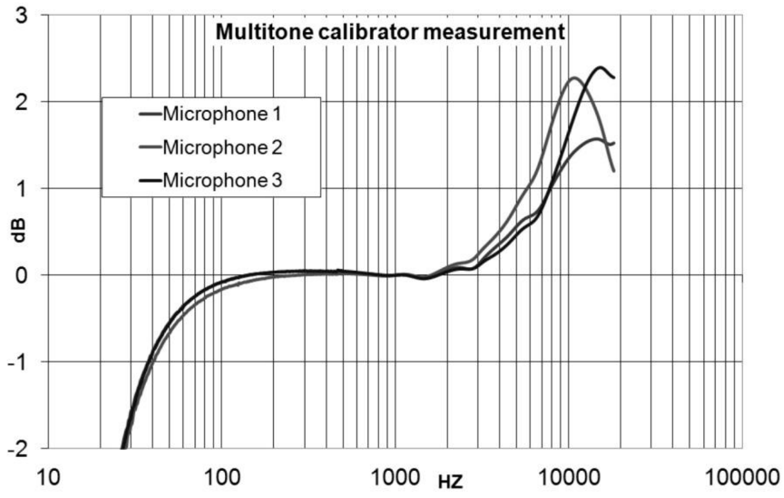
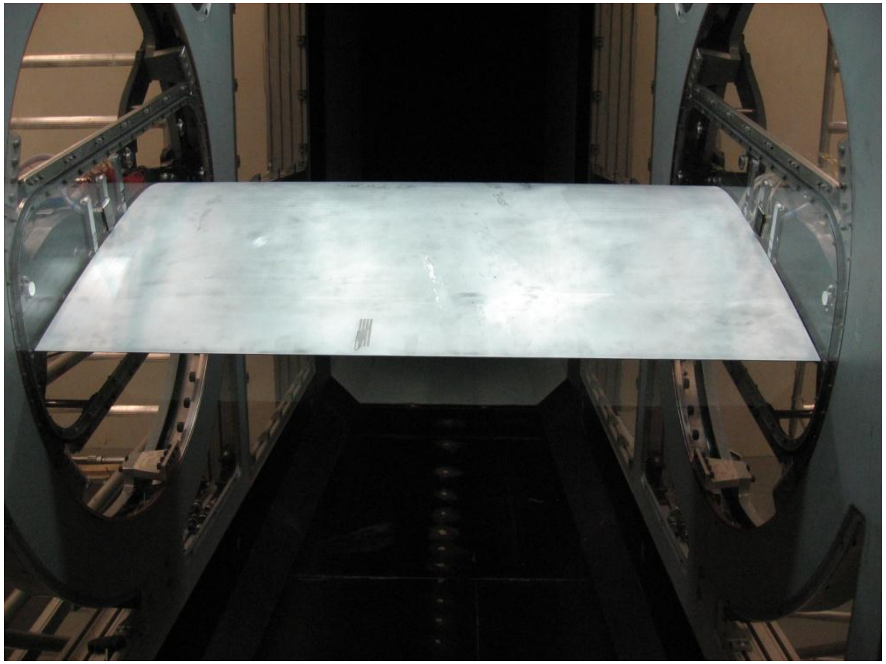


Figure 4: High-Frequency Microphones Deviations [Figure courtesy of Brüel & Kjær]

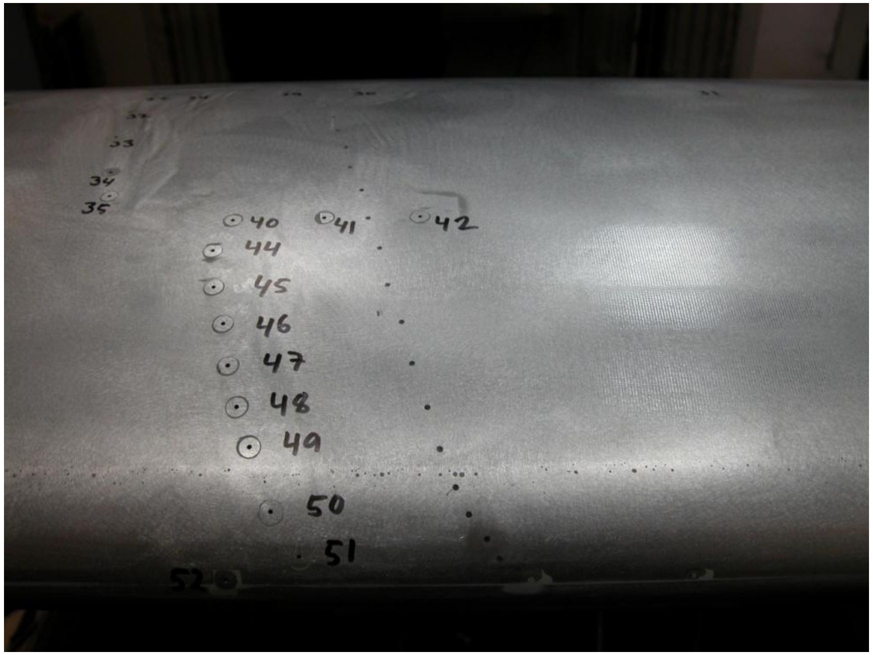
Wind tunnel measurements compared with model results

Test in the LM Wind Tunnel - 2007

Aerodynamic Test Facility

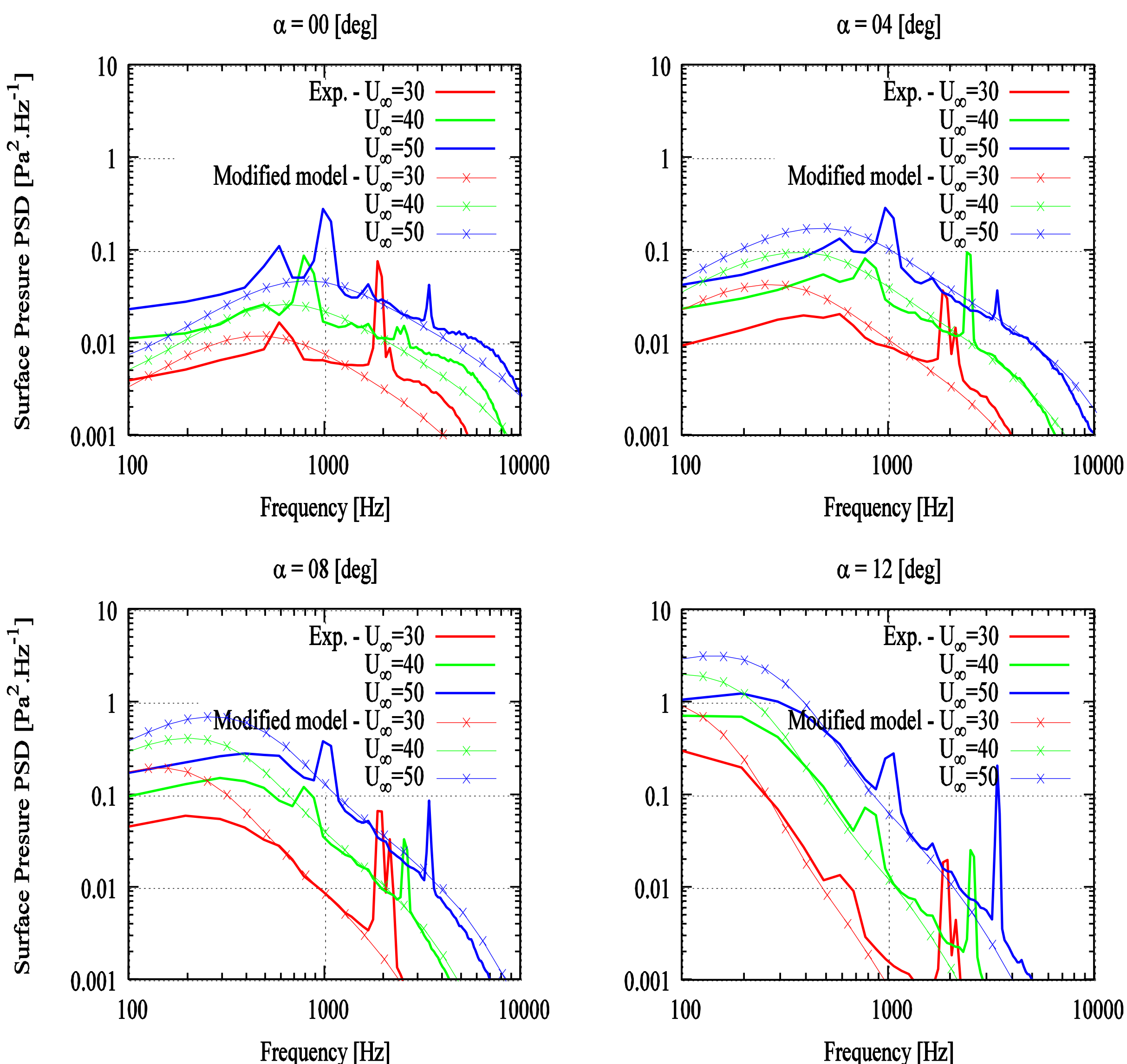


NACA0015 Airfoil Section

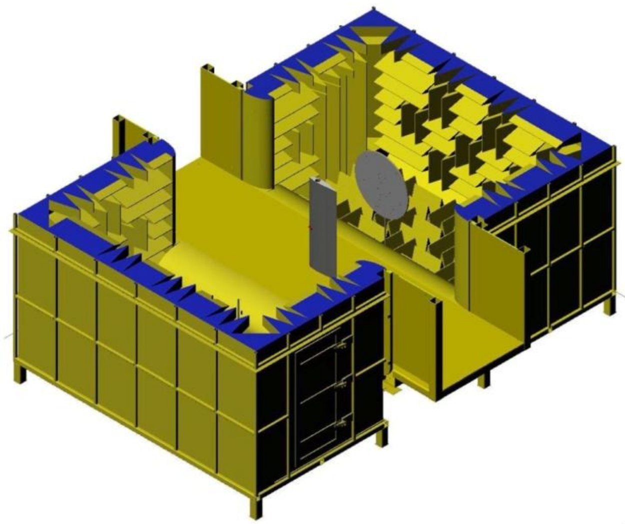


Surface Pressure Measurement Holes

Surf. Pres. Measurements near TE



Virginia Tech measurements 2011*
- NACA64-618 airfoil with microphones



Can we transfer SP to far field sound ?

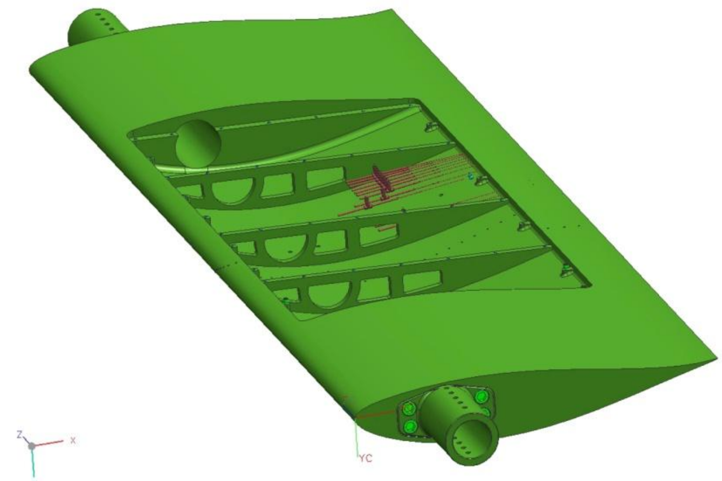


Figure 3.6: CAD rendering of NACA64-618 airfoil with open lid and view on the instrumentation (red: microphone tube adapters)

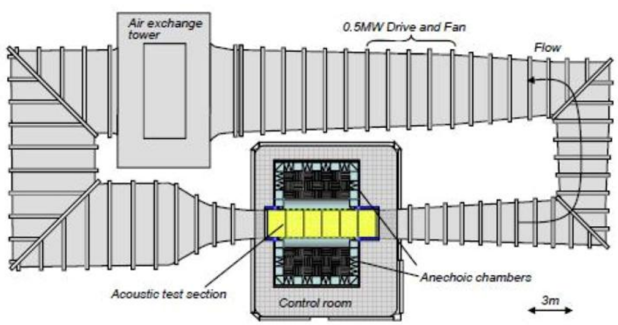
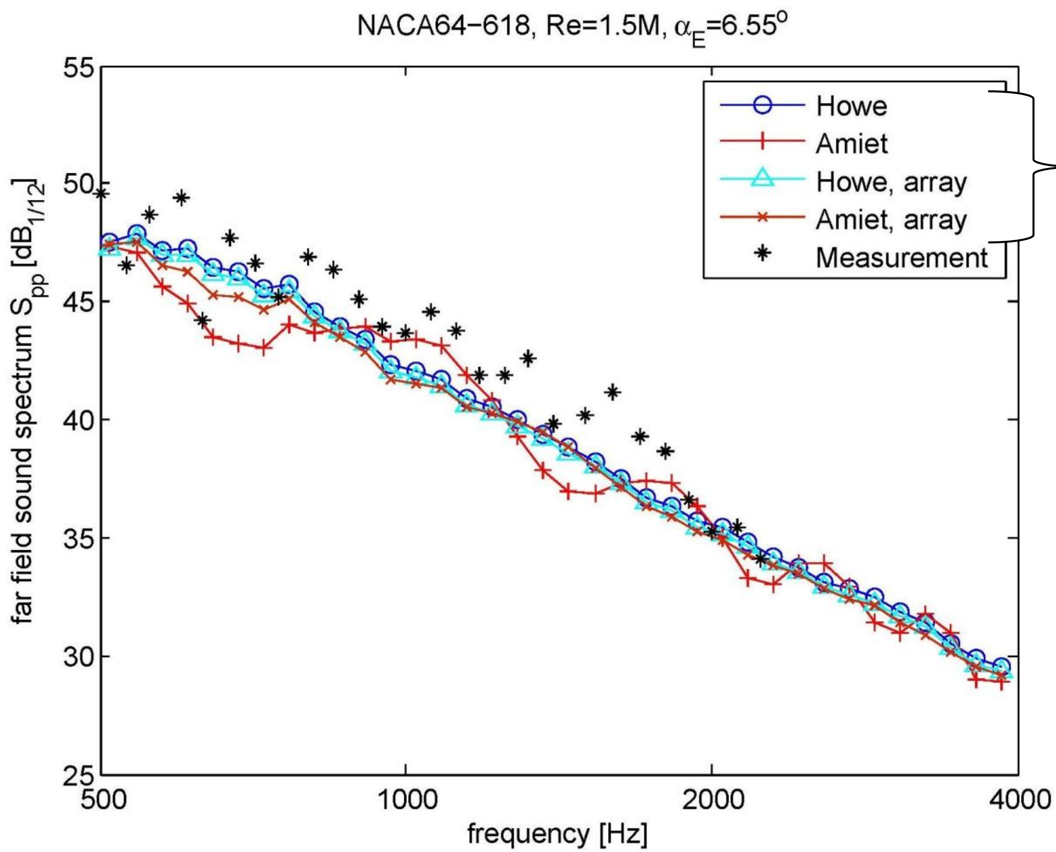


Figure 3.4: Schematic of the Virginia Tech Stability Wind Tunnel in acoustic configuration from [37]

* PhD thesis report by Andreas Fischer (2011) "Experimental characterization of airfoil boundary layers for improvement of aeroacoustic and aerodynamic modeling "

Virginia Tech measurements 2011*
- NACA64-618 airfoil with microphones



Derived from SP measurements

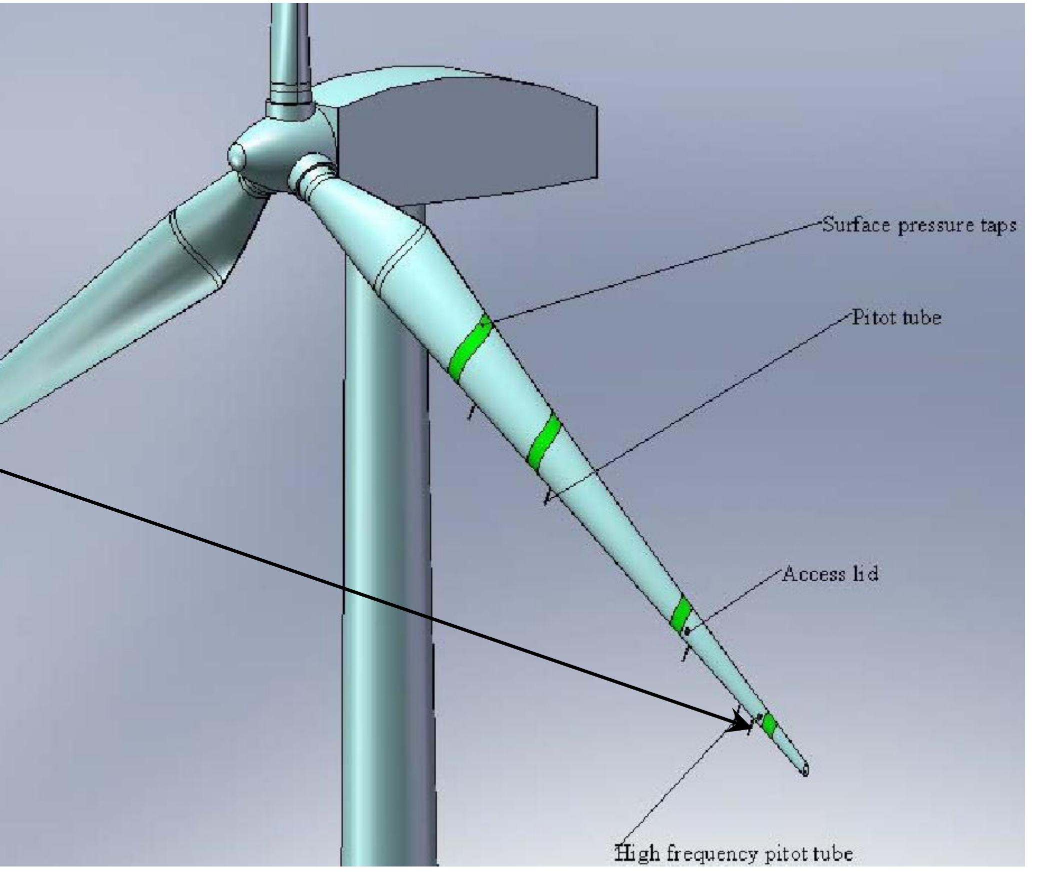
* PhD thesis report by Andreas Fischer (2011) “Experimental characterization of airfoil boundary layers for improvement of aeroacoustic and aerodynamic modeling ”

Measurements on a full scale 80m diameter rotor

- From the DAN-AERO project -

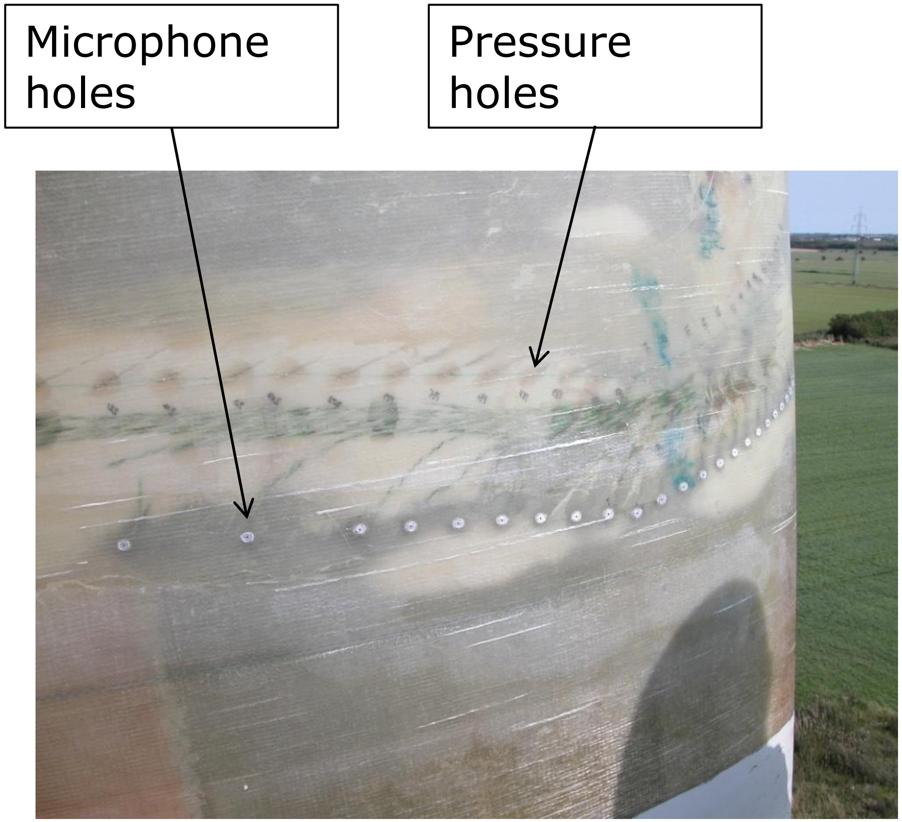
Measurement of SP on a full scale rotor blade, 80m diameter rotor, 2MW - - DAN-AERO MW project

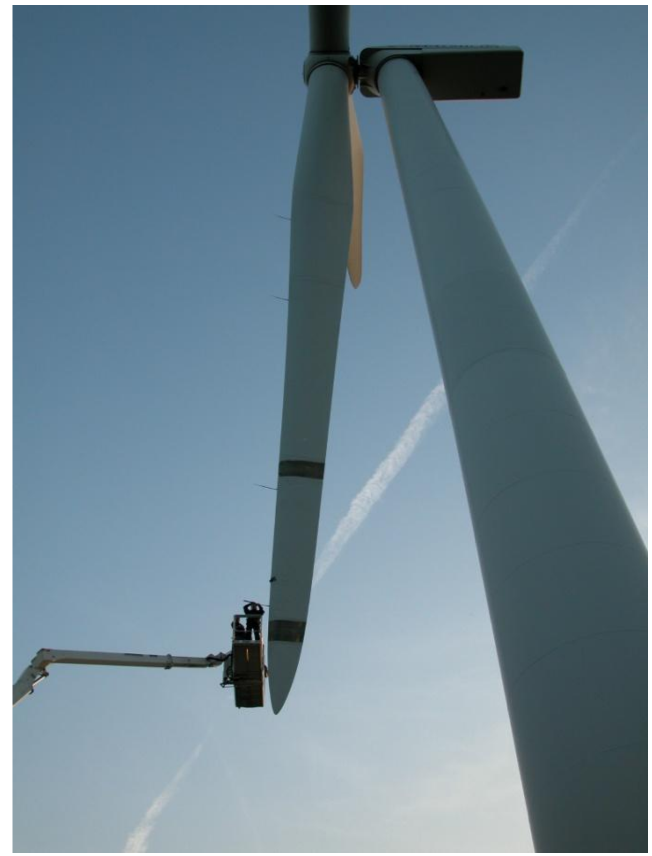
- surface pressure and inflow measured at 4 radial stations
- **the outboard station also instrumented with around 60 microphones for high frequency surface pressure measurements**
- high frequency measurements of the inflow
- measurements from June to September 2009



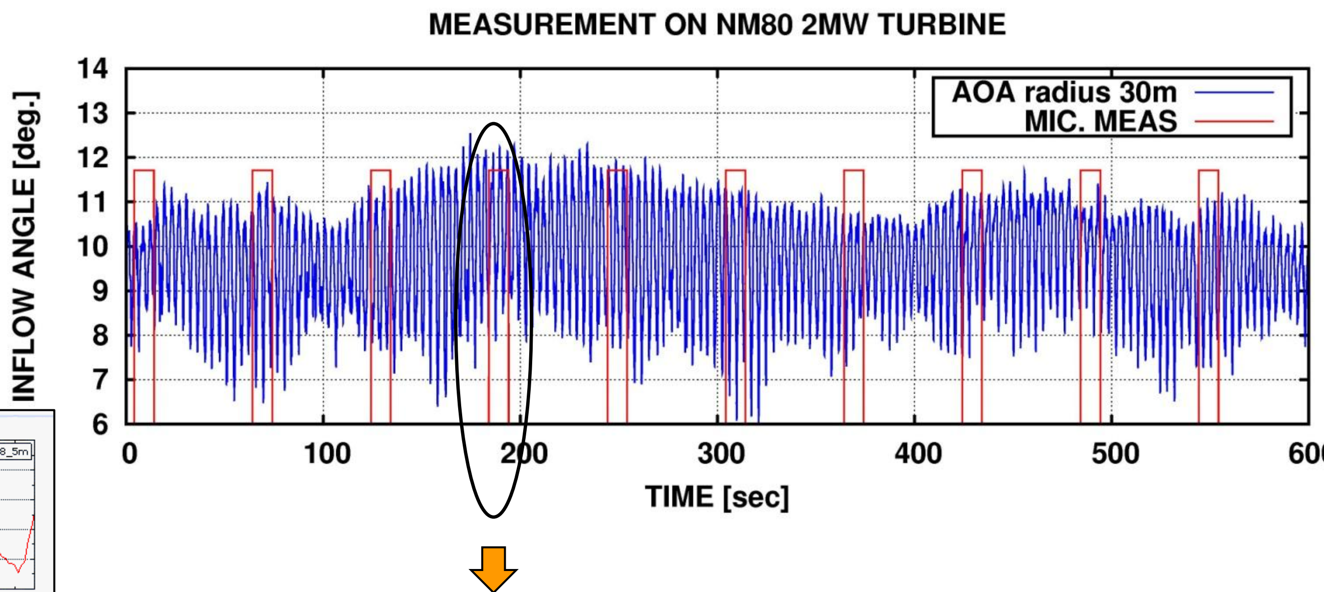
Installation of the 38.8m instrumented blade in May 2009

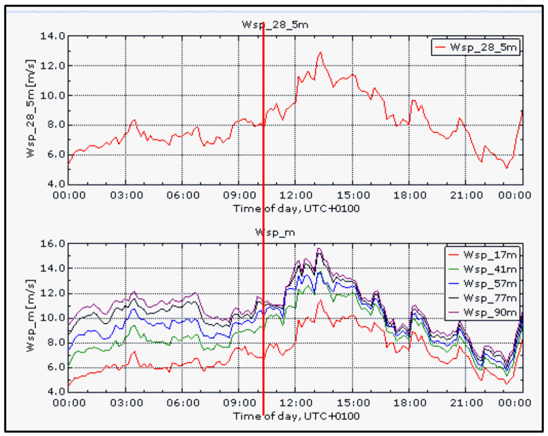
Campaign measurements from June to September 2009

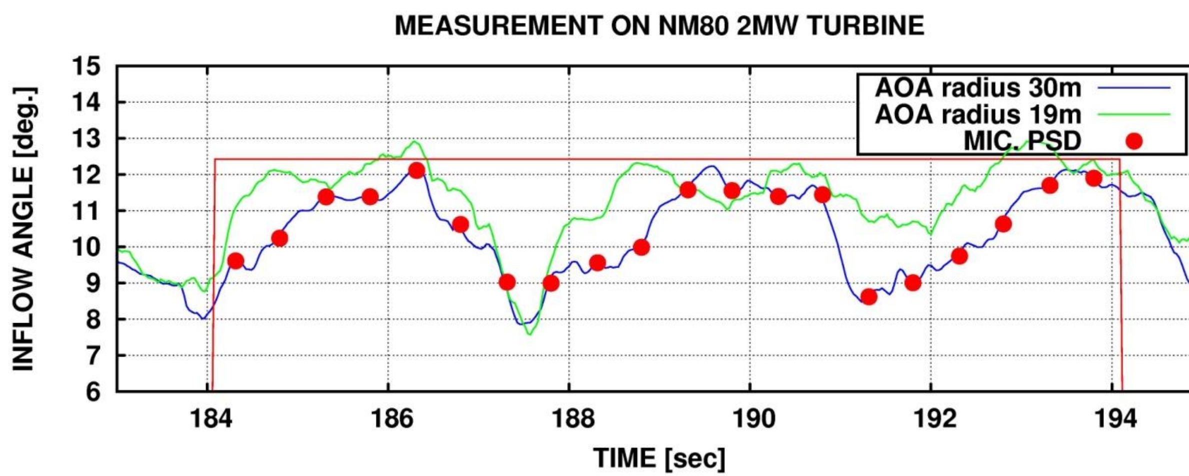




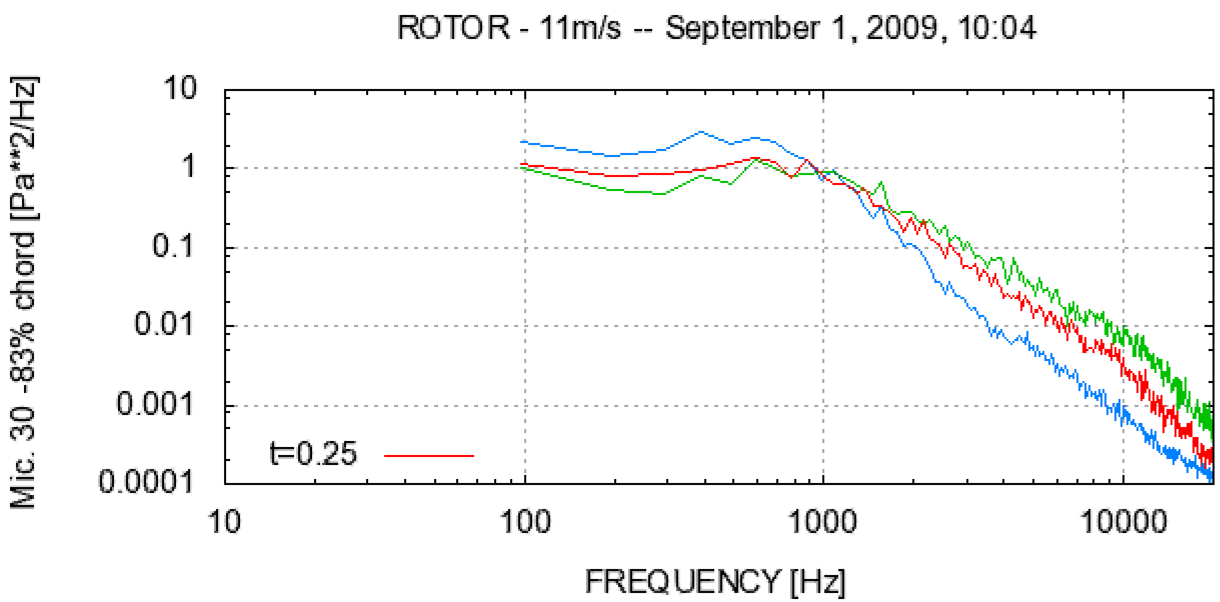
Measurement of SP on a full scale rotor blade, 80m diameter rotor, 2MW





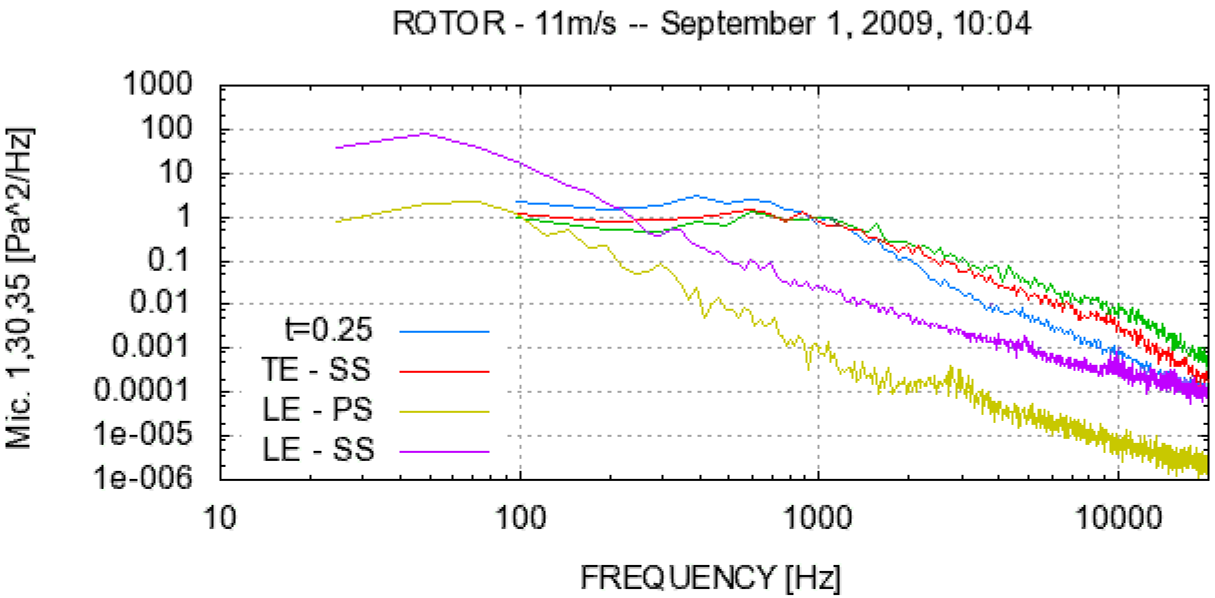


TE spectra measured during free inflow at 9-11m/s



Each spectrum is based on 0.5sec

TE + LE spectra measured during free inflow at 9-11m/s



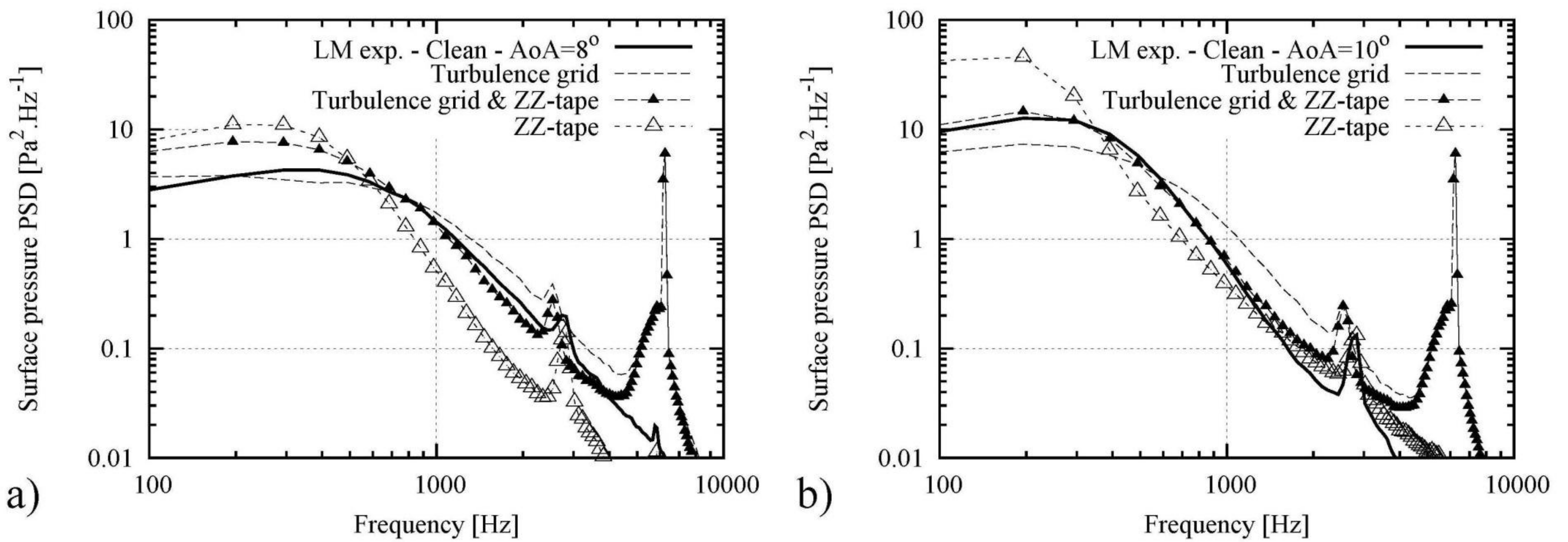
Each spectrum is based on 0.5sec

Influence of different inflow conditions on the noise source

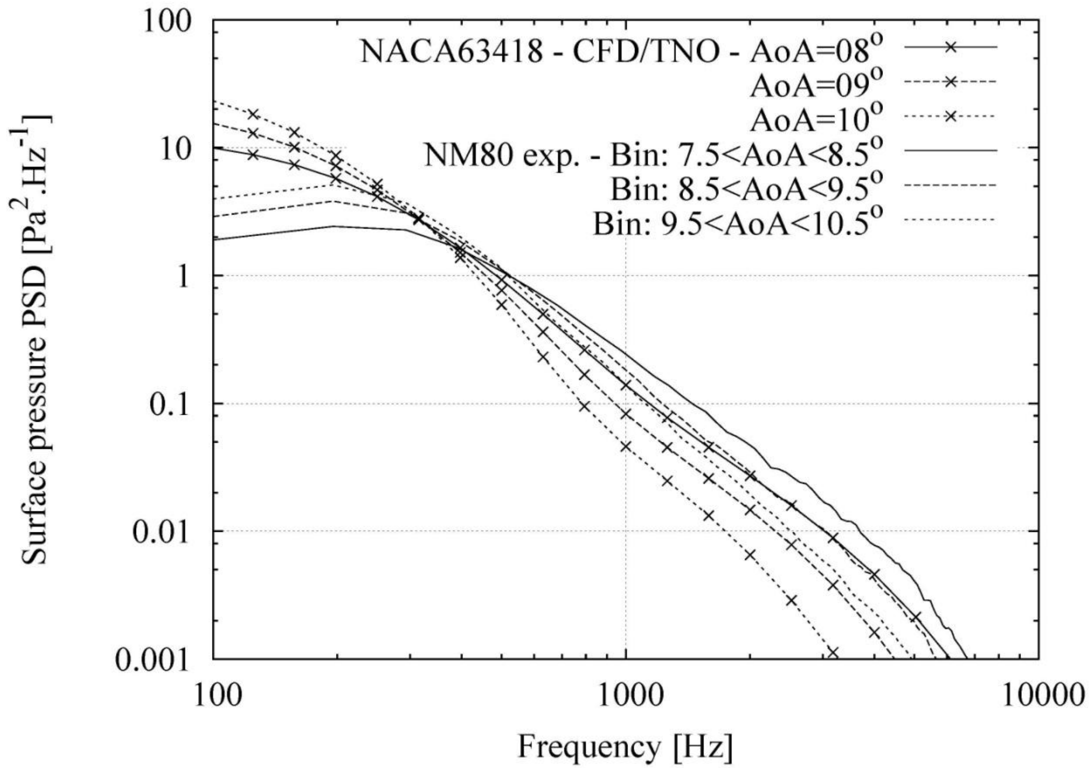
Influence of turbulence in inflow ?

- turbulence grid in wind tunnel
- increased turbulent inflow to rotor due to wake operation

Influence of turbulence in inflow ?



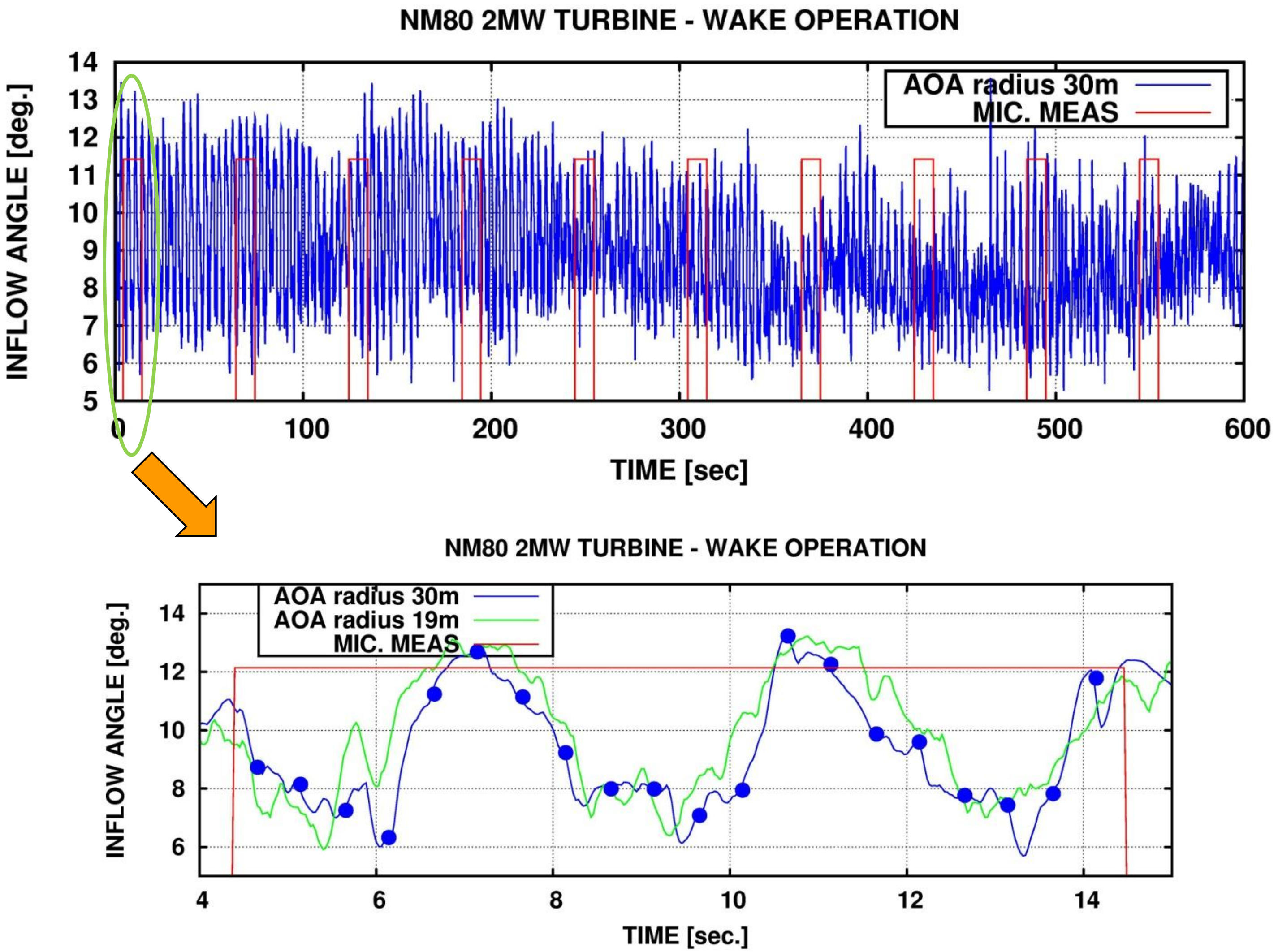
Deviations due to influence of turbulence in inflow ?



(b) SP Spectra near TE ($x/C = 93\%$, Suction side)

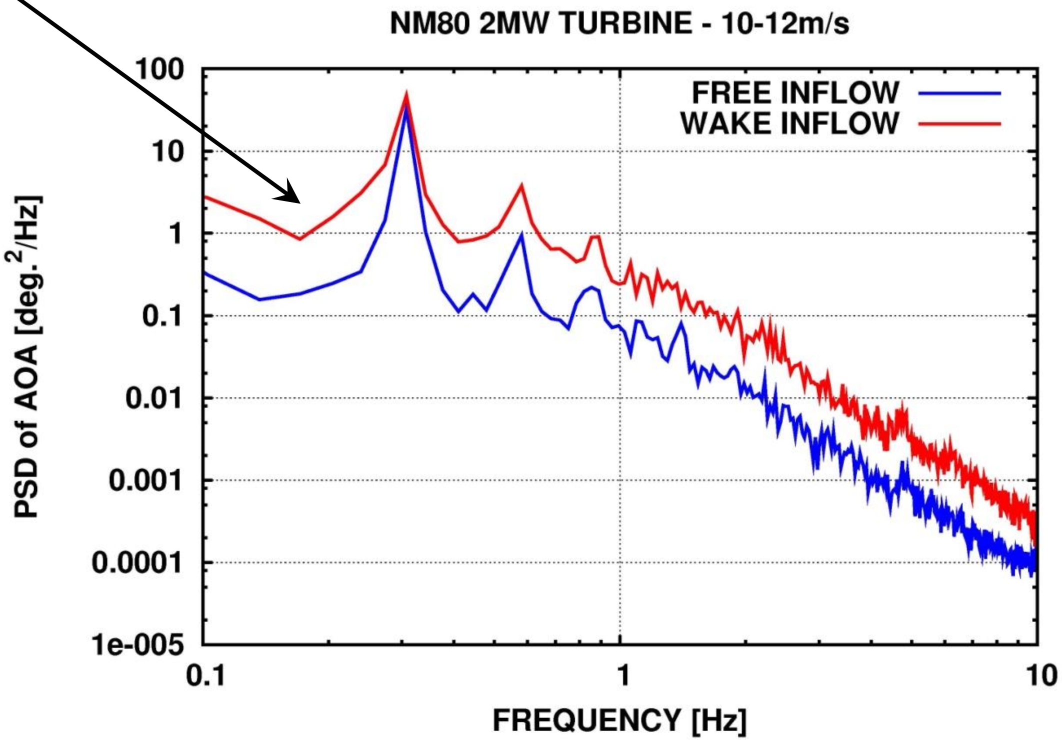
Figure 9: NM80 Rotor (vs. CFD/TNO Model for SP near TE) - Influence of AoA

Influence of wake operation
- distance to upstream turbine 3.5D

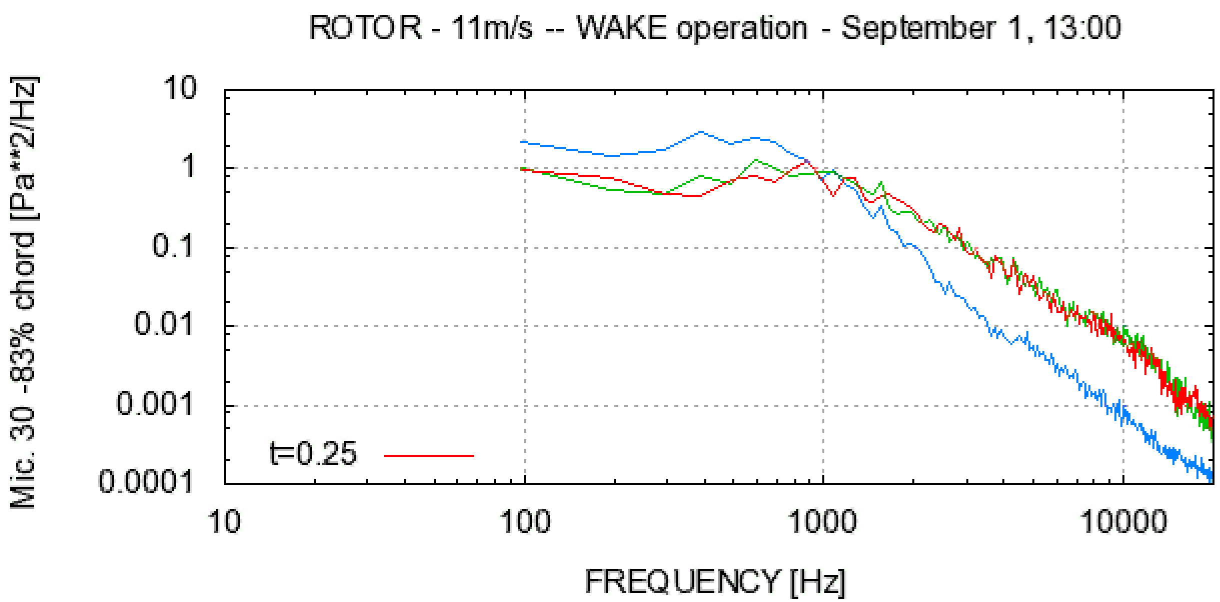


Influence of wake operation
- distance to upstream turbine 3.5D

Increased turbulence level increases AOA variations

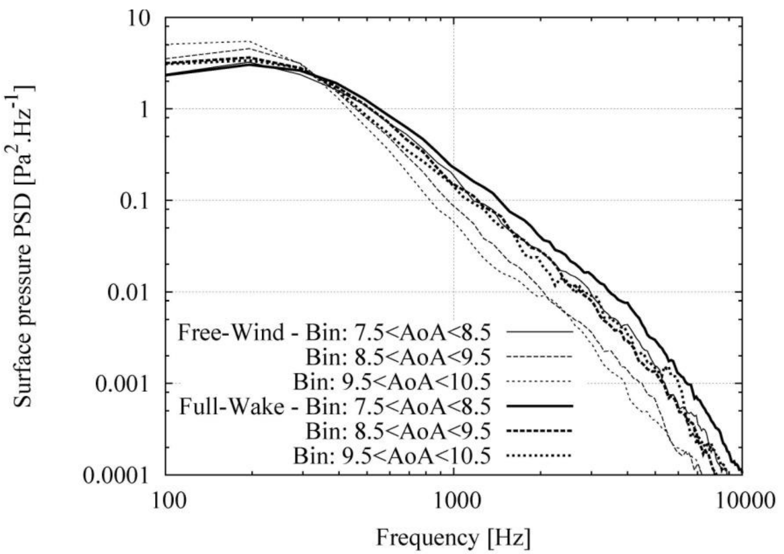


Influence of wake operation
- distance to upstream turbine 3.5D



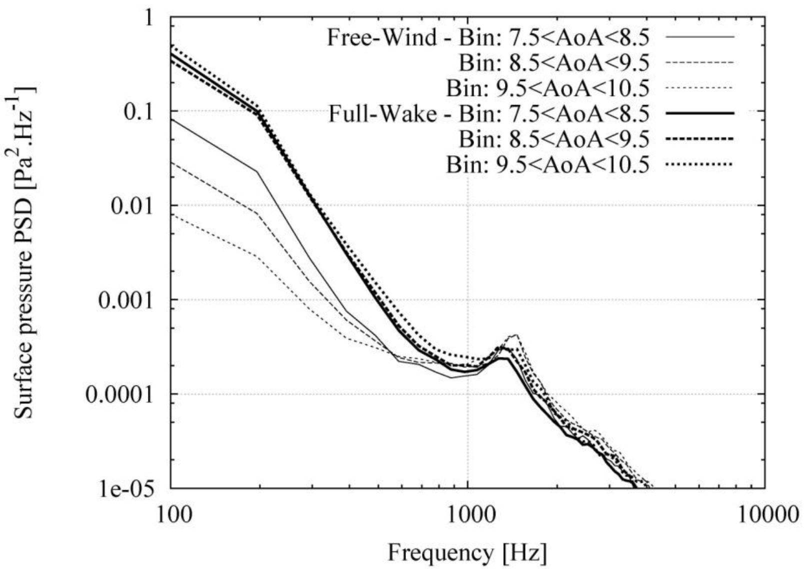
Influence of wake operation - distance to upstream turbine 3.5D

Trailing edge



(b) TE Microphone - $x/C = 93\%$ (Suction side)

Leading edge



(a) LE Microphone - $x/C = 2.2\%$ (Pressure side)

Perspectives for application of the technique

A blade mounted sensor system for aeroacoustic noise source monitoring and control

Objectives of blade mounted monitoring system:

- continuous monitoring of the noise source by measuring HF SP at a few points on each blade

  - derive total noise of turbine based on numerical modelling and experimental calibration

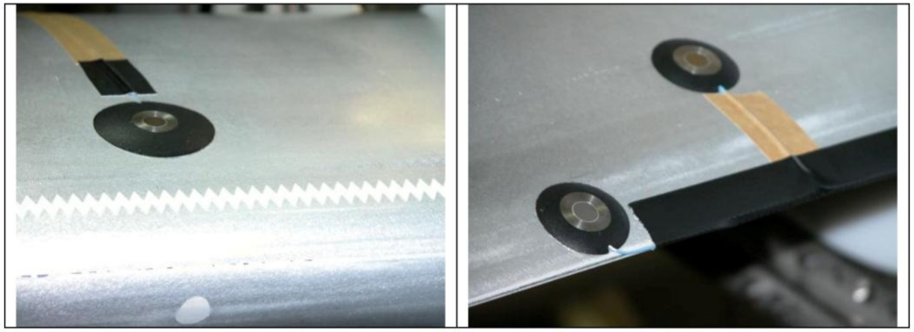
  - derive details of noise source variation as function of blade position

Advantages of system

- Detailed and continuous source monitoring enables changes of turbine control system only when necessary

- Detailed source monitoring can provide input to the control system on an azimuth level, e.g. for individual pitch control to reduce/avoid amplitude noise modulation

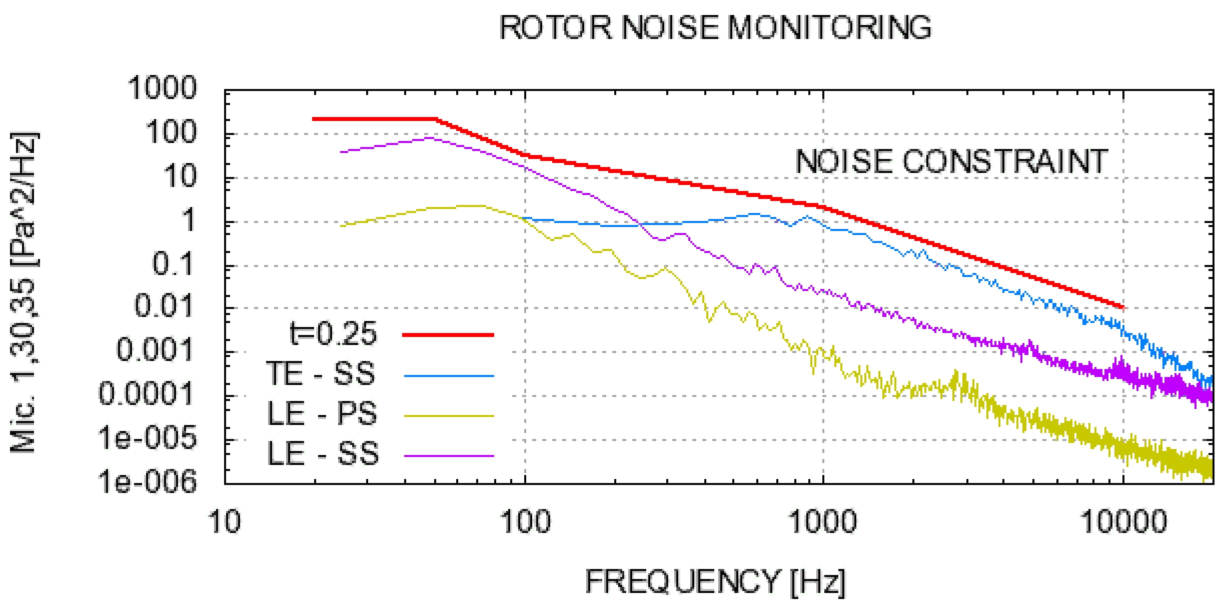
Proposed system



Surface mounted microphones from B&K

Data processing and analysis system

One output screen from the system could be continuously updated PSD spectra of surface pressure fluctuations



Acknowledgements

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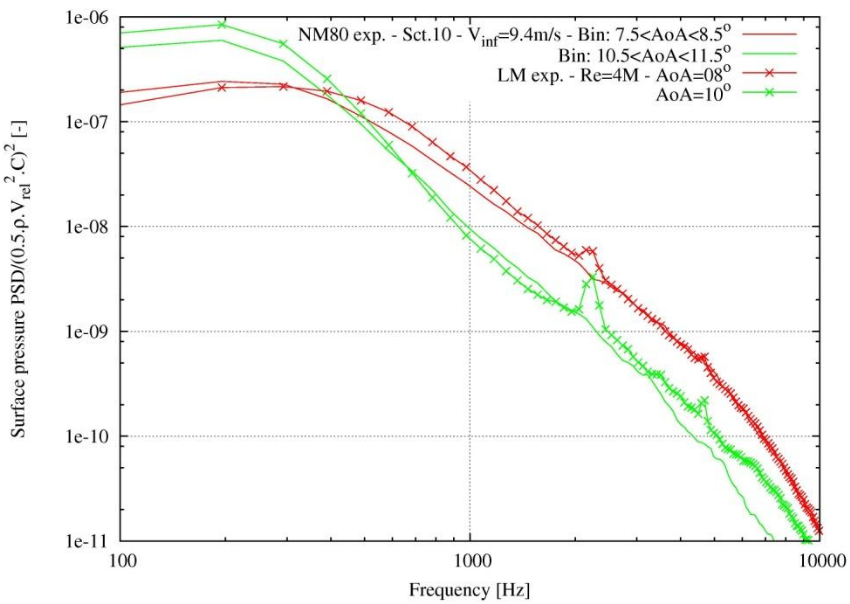
Partly by the project participants:

- Siemens
- Vestas
- LM Wind Power
- Dong Energy
- DTU Wind Energy

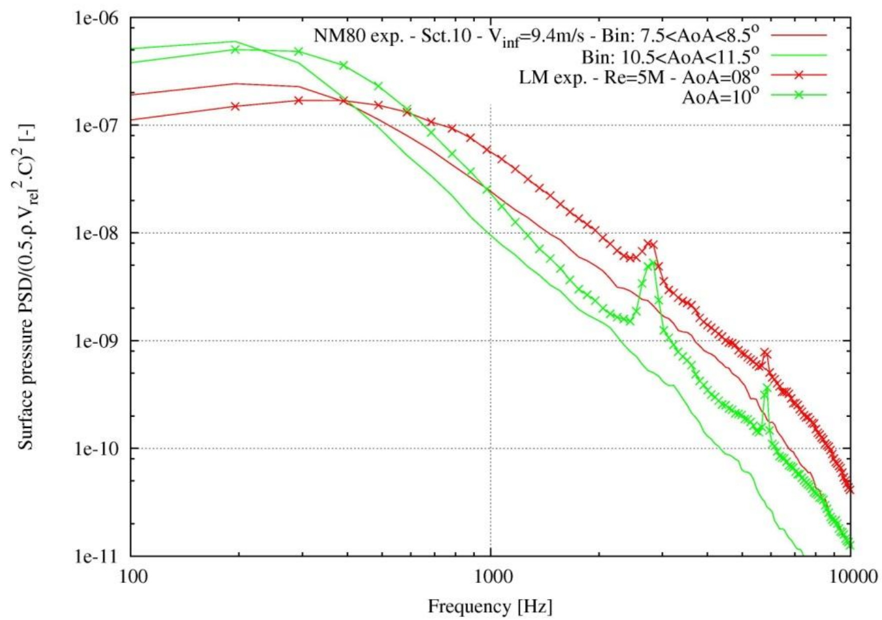

Thank you for
your attention

Comparison of SP measured in wind tunnel and on the NM80 2MW rotor - preliminary

difference in Re number



same Re number



c=0.9m – wind tunnel airfoil model
c=1.2m - rotor